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BUILDING COMPONENTS AND BUILDINGS

Life cycle assessment of a large, thin ceramic tile with advantageous technological properties

Martina Pini · Anna Maria Ferrari · Rita Gamberini · Paolo Neri · Bianca Rimini

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Abstract
Purpose Ceramic tiles play a strategic role in the Italian market; currently, the Italian production is of 367.2 million m^2 (Confindustria Ceramica 2012). In 2009, Italy was positioned as the world's fourth largest producer of ceramic tiles, producing 368 million m^2 of the world's total production of 1,735 million m^2 Giacomini (Ceram World Rev 88:52–68, 2010). Therefore, there is an ongoing effort to create innovations in the products offered and their manufacturing processes, in order to better compete on the market and to create eco-friendly products. Recently, the Italian Ceramic District has increased its focus on environmental issues with the aim of protecting natural resources and reducing the energy and material consumption. For this reason, a new product was born in the Italian Ceramic District, namely, a large thin ceramic tile (dimensions 1,000 mm× 3,000 mm×3.5 mm) reinforced with a fibreglass backing, which gives the product excellent resistance and flexibility properties. The aim was to manufacture a new product with lower environmental impact than the traditional one. The production of a large thin ceramic tile requires, in fact, a lower quantity of materials, transports and energy consumptions comparing to the same metres square of traditional ceramic tile. At the present, no comparative life cycle assessment (LCA) studies have been performed between traditional and innovative ceramic stoneware tiles. This study analyses, for the first time, a life cycle of the innovative ceramic product (porcelain stoneware) developed by a company of the Italian Ceramic District.
Methods The analysis is performed using the LCA methodology, in order to identify environmental impacts, energy consumption and CO_2 equivalent emissions that occur during extraction of raw materials, transportation, production, material handling, distribution and end-of-life stages within a cradle to grave perspective.
Results and conclusions LCA analysis indicates that the highest environmental impact mainly affects the respiratory inorganics impact category due to base slip production (27.62 %), caused by the transport of the raw materials and by non-renewable impact category due to both the pasting phase (21.31 %) and the two-component adhesive manufacture. The major greenhouse gas (GHG) emissions are related to the production of polyurethane, a component of the adhesive used in the pasting stage, and to the natural gas consumption in the firing process.

Keywords CO_2 equivalent emission · Impact assessment · Large thin ceramic tile · Life cycle assessment

1 Introduction and literature review

Ceramic tiles are widely used as building materials. It has been estimated that the contribution of all types of ceramic materials included in a building constitutes about 50 % of all the materials used. The manufacture of such products, from raw material extraction and processing to forming and transportation, inevitably consumes natural resources and causes various types of environmental impact (Giacomini 2010; Tikul and Srichandr 2010).

The analysis of these products may be performed using various methodologies. Among them, the life cycle assessment (LCA) is the best regarded and constitutes a suitable instrument for environmental decision support (Vince et al. 2008).

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M. Pini (✉) · A. M. Ferrari · R. Gamberini · P. Neri · B. Rimini
Department of Engineering Sciences and Methods,
University of Modena and Reggio Emilia, Via Amendola, 2,
42100 Reggio Emilia, Italy
e-mail: martina.pini@unimore.it

Several LCA studies of indoor and outdoor covering materials are proposed in the literature: environmental profile comparison of the single-fired ceramic and marble tile (Nicoletti et al. 2002); environmental impact assessment of bricks produced and used in Greece (Koroneos and Dompros 2007); life cycle analysis of single-fired, glazed tile and stoneware (Bovea et al. 2010; Ibáñez-Forés et al. 2011); the first LCA study of a typical Sicilian marble slabs and tiles (Perlato di Sicilia) (Traverso et al. 2010); and sensitivity analysis to assess the uncertainty in LCA, considering a case study of a typical roof tile employed in restoring old buildings in the Mediterranean area (Cellura et al. 2011). Table 1 shows a literature review carried out on the LCA methodology applied to covering materials and detailing the examined material, the system boundaries, the phases excluded from the study and the characteristics of the studied material.

The year 2009 was of the first real slowdown for the Italian tile industry. With the crisis of 2008, Italian tile production registered a significant fall, causing a decrease of 28.2 % in production at the end of 2009 (Giacomini 2010). Nevertheless, the ceramic industries invested in research into the analysis of the most profitable production processes (Gamberini and Regattieri 2008) along with research into handling the current situation. The quality of the existing products improved (Schabbach et al. 2007; Bondioli et al. 2009), and some innovations were proposed that increase the number of possible application fields (embellishment of indoor settings, furnishing elements, outdoor coatings and floors, photovoltaic panel gallery, curtain walls or ventilated walls).

This study considers an innovative ceramic stoneware slab of only 3.5 mm thick that is reinforced with a fibreglass backing. Besides having similar properties to traditional ceramic tiles in its aesthetic, mechanical, chemical and structural properties, this new product also exhibits advanced technological proprieties, such as perfect flatness and a high degree of flexibility (bending strength is 50 N/mm^2 vs traditional ceramic tiles that register a value of 30 N/mm^2). Table 2 shows its physical and chemical properties.

The aim of this paper is to conduct a life cycle assessment study on this type of innovative ceramic tile with a thin thickness and large dimensions, an example of which is produced by Laminam S.p.A. (part of the System Group) in the Sassuolo ceramic district (Italy). According to the ISO 14040, 44, the potential energy consumption and the amount of greenhouse gases (GHGs) expressed as CO_2 equivalents have been identified (Jönsson et al. 1997, 1999). The life cycle comprises various stages: (1) supply of the raw material, (2) atomisation, (3) pressing, (4) application of serigraphy product, (5) application of engobe, (6) firing, (7) first sorting, (8) gluing of the fibreglass, (9) dry cutting, (10) final sorting and packaging, (11) storage, (12) delivery to consumers and (13) the end of life of the ceramic tile. Moreover, for each stage, the material handling by a laser-guided vehicle (LGV) and intermediate storage into automatic storage (AS) have been evaluated.

Initially, tiles reinforced with a fibreglass backing applied the back using a special adhesive are produced with large dimensions (1,000 mm × 3,000 mm × 3.5 mm) and a specific weight of 8.2 kg/m^2. Subsequently, they are cut into a 1,000 mm × 1,000 mm format.

In an LCA study, the quality and credibility of the results depends largely on the quality of the data included in the life cycle inventory (LCI) stage. According to ILCD handbook (European Commission 2010), the inventory must state, in a specific and reliable way, all the inputs in the form of material and energy resources and the outputs in the form of air emissions, emissions into water and soil as well as the solid waste that is generated for each of the stages of the life cycle of the system being studied (ISO/TS 14048). Drawing up an LCI is the costliest task in an LCA study due to the large amounts of resources that are required (especially time) in order to obtain up-to-date and reliable information (Nicoletti et al. 2002).

2 Life cycle of a large, thin ceramic tile reinforced with a fibreglass backing

The entire life cycle of a large thin ceramic tile is shown in Fig. 1. It consists of six main steps: (1) green tile production (where the main actions include the supply and treatment of raw materials), (2) firing, (3) pasting, (4) cutting, (5) packaging and final distribution and, finally, (6) the end of life that is studied.

2.1 Green tile production

The raw materials used for the manufacture of the tiles are clay, feldspars, water, pigment and deflocculant. Clay and feldspars are extracted from mines and then transported by road and by sea to the factory where they are stored. The water consumed comprises 50 % rainwater and 50 % tap water, while the deflocculant and the pigment are transported from the producer to the company. The former is produced 20 km away, while the latter is made in Spain.

The raw materials are then loaded into three hoppers in order to obtain the composition reported in Table 3.

The mixture is then transported via a conveyor belt to a wet mill for preparation of the slurry. In order to produce the large, thin ceramic tile that is the subject of this paper, it is necessary to prepare two different slurries: a base and a coloured slip. The first is created by wet milling of clay, feldspar, water and deflocculant. The slurry obtained has a homogeneous composition and a good grain size distribution. The second is a mixture consisting mainly of iron–chromium oxide ceramic pigments, which give the colour to slurry, clay and water. The coloured slip is added to the base slip during the atomisation phase. The ceramic slip with 34.5 % moisture is spray dried in

Table 1 Literature review

LCA studies	Country of origin	Final product	Functional unit	System boundaries	Phases excluded from the life cycle	Average density	Thickness	Lifetime (years)
Potting and Blok (1995)	Netherlands	Linoleum	1.064 m^2	From cradle to grave	• Installation • Use phase (in the use phase, the study includes only the energy requirement for vacuum cleaning)	2.3 kg/m^2	n/a	8
		Cushion vinyl	1.995 m^2			1.7 kg/m^2		
		Tufted carpet with a woollen pile	1.995 m^2			2.6 kg/m^2		
		Tufted carpet with a polyamide pile	1.995 m^2			2.25 kg/m^2		
Günther and Langowski (1997)	Netherlands	PVC	20 m^2	From cradle to grave (the use phase is treated separately from the rest of the whole life cycle)	• Emissions during the use phase		2–2.5 mm	20
		Cushioned PVC					1.7–3 mm	
		Polyolefin					2 mm	
		Rubber					2–3.2 mm	
		Linoleum					2–2.5 mm	
Jönsson et al. (1997, Jönsson 1999)	Sweden	Linoleum	1 m^2	From cradle to grave	• Cleaning and maintenance in the use phase • Energy consumption of the use phase	2.3 kg/m^2	2 mm	25
		Vinyl flooring				1.3 kg/m^2	2.3 mm	20
		Pine wood flooring				7 kg/m^2	25 mm	40
Nicoletti et al. (2002)	Sassuolo Emilia Romagna Italy	Single-fired, glazed ceramic tile	1 m^2	From cradle to grave	• Installation (material to fix the tiles) • Use phase • Emissions coming from the neutralisation of the exhausted lime from the abatement of the combustion fumes • Sludge coming from the treatment of the waste water	18 kg/m^2	n/a	20
	Massa Carrara Tuscany Italy	Marble tile	1 m^2	From cradle to grave	• Installation (material to fix the tiles) • Production and consumption of floor wax used during the tile life • Production, use and disposal of the diamond wire	48.6 kg/m^2	18 mm	40
Koroneos and Dompros (2007)	Sindos Thessaloniki Greece	Clay brick	1 ton (168 units of bricks) Brick sizes, 17×14×28 cm	From cradle to gate	• Installation • Use phase	5.945 kg/brick	140 mm	80

Table 1 (continued)

LCA studies	Country of origin	Final product	Functional unit	System boundaries	Phases excluded from the life cycle	Average density	Thickness	Lifetime (years)
Bovea et al. (2010)	Castèllon Spain	Single-fired, glazed tile	1 m^2	From cradle to gate	• Installation • Use phase • End-of-life steps	n/a	n/a	n/a
Tikul and Srichandr (2010)	Thailand	Double-fired, glazed tile	1 Mg (megagram)	From gate to gate	• Extraction and production of raw material • Machinery and equipment in the plant • Distribution • Installation • Use phase • Maintenance • End of life	10.57 kg/m^2	5 mm	n/a
Traverso et al. (2010)	Custonaci Sicily Italy	Sicilian marble slabs and tiles (Perlato di Sicilia)	1 m^2	From cradle to gate	• Use phase • End of life • Production, use and disposal of diamond wire	Commercially sized blocks, $3\times1.8\times$ 1.5 m	1.5 m is the block's height (commercially sized blocks, 3×1.8 $\times1.5$ m) which will be cut into slabs and tiles	n/a
Cellura et al. (2011)	Sicily Italy	"Sicilian tiles"	1,000 kg	From cradle to gate	• Installation • Use phase • End of life	n/a	n/a	n/a
Ibáñez-Forés et al. (2011)	Spain	Single-fired, glazed stoneware	1 m^2	From cradle to grave	• Use phase	17.23 kg/m^2	n.a.	20
Present Study	Fiorano Modenese, Emilia Romagna, Italy	Large, thin ceramic (porcelain stoneware) tile reinforced with fibreglass backing	1 m^2	From cradle to grave	• Installation • Use phase	8.2 kg/m^2	3.5 mm	n/a

n/a not available

Table 2 Physical and chemical properties of a large, thin ceramic tile with fibreglass backing vs a traditional ceramic tile

Physical and chemical properties	Large, thin ceramic tile with fibreglass backing	Traditional ceramic tile
Size	1,000 mm×3,000 mm	600 mm×600 mm
Thickness (mm)	3.5	9
Weight (kg/m^2)	8.2	19
Water absorption (%)	Average value 0.1	Average value 0.2
Bending strength in N/mm^2	Average value 90	Average value 35
Mohs scale hardness	≥6	6
Resistance to deep abrasion (mm^3)	≤175	≤130
Coefficient of linear thermal expansion (10^{-6}/°C)	6.6	6.5
Resistance to thermal shock	Resistant	Resistant
Chemical resistance	No visible effect	No visible effect
Stain resistance	Class 5	Class 5
Shock resistance	Average value 0.8	Average value 0.75
Coefficient of friction	R9	R9

order to obtain a powder with suitable grain size and humidity for pressing (about 4.5 %).

The atomised material is then transformed into a green ceramic slab (size 3,345 mm×1,150 mm) through the use of an innovative press system without the use of moulds. After pressing, the green ceramic slab is trimmed to 3,300 mm×1,125 mm. The scraps from the process are transported with a pump into a silo and then handed over to an authorised factory for the treatment of inerts. Screen paste and engobe are then applied to the green slab, with the aim of improving its surface quality.

2.2 Firing

Thermal treatments are performed in a hybrid kiln, where the following steps occur:

– pre-heating, from room temperature to 1,100 °C
– firing step at 1,220 °C temperature for about 30 min
– cooling

After operations involving the kiln, the ceramic slab measures 3,090 mm×1,030 mm. Tiles are then transferred by LGVs to automatic storage, where they stay for at least 48 h. Subsequently, LGVs transfer slabs from the automatic storage to the first sorting line, where they are checked and sorted by shade and surface quality. Scrap and waste tiles are collected in bins and transported to a collection place. Finally, they are handed over to an authorised company for the treatment of inerts.

2.3 Pasting of fibreglass

Pasting is executed by an automated process, where a fibreglass backing is applied to the back of the tile. The fibreglass gives the slab greater sturdiness, lightness and elasticity. The pasting line includes the first unloading where the tile is conveyed by the metal platform to the conveyor belt, then covered by a protective film on the tile's "fair-faced" surface. Slabs are then passed into a horizontal electric heater (operating in a range of 37–40 °C) to stabilise the temperature of the material to be processed. The tile is then sprayed with a two-component adhesive in a booth with a pressurising system, and the adhesive residues that are collected are transported away using a paper carpet. Adhesive is batched, thanks to a fully automated system that ensures a homogeneous mix of both components. Fibreglass is then applied to the slabs, and possible offsets are automatically removed. Then, a tooled anthropomorphous robot carries out the squeegeeing to prevent irregular air spots on the surface. Then, the first catalysation step between the bonding agent and slab is performed in a vertical drier (60–80 °C). The tile rests for 15 min, then the protective film is removed, and the slab is loaded automatically onto the tray.

The two-component adhesive, paper and protective film waste are collected and disposed of as hazardous waste through incineration. The dust generated from the pasting process is caught by an air filter and disposed of as municipal solid waste.

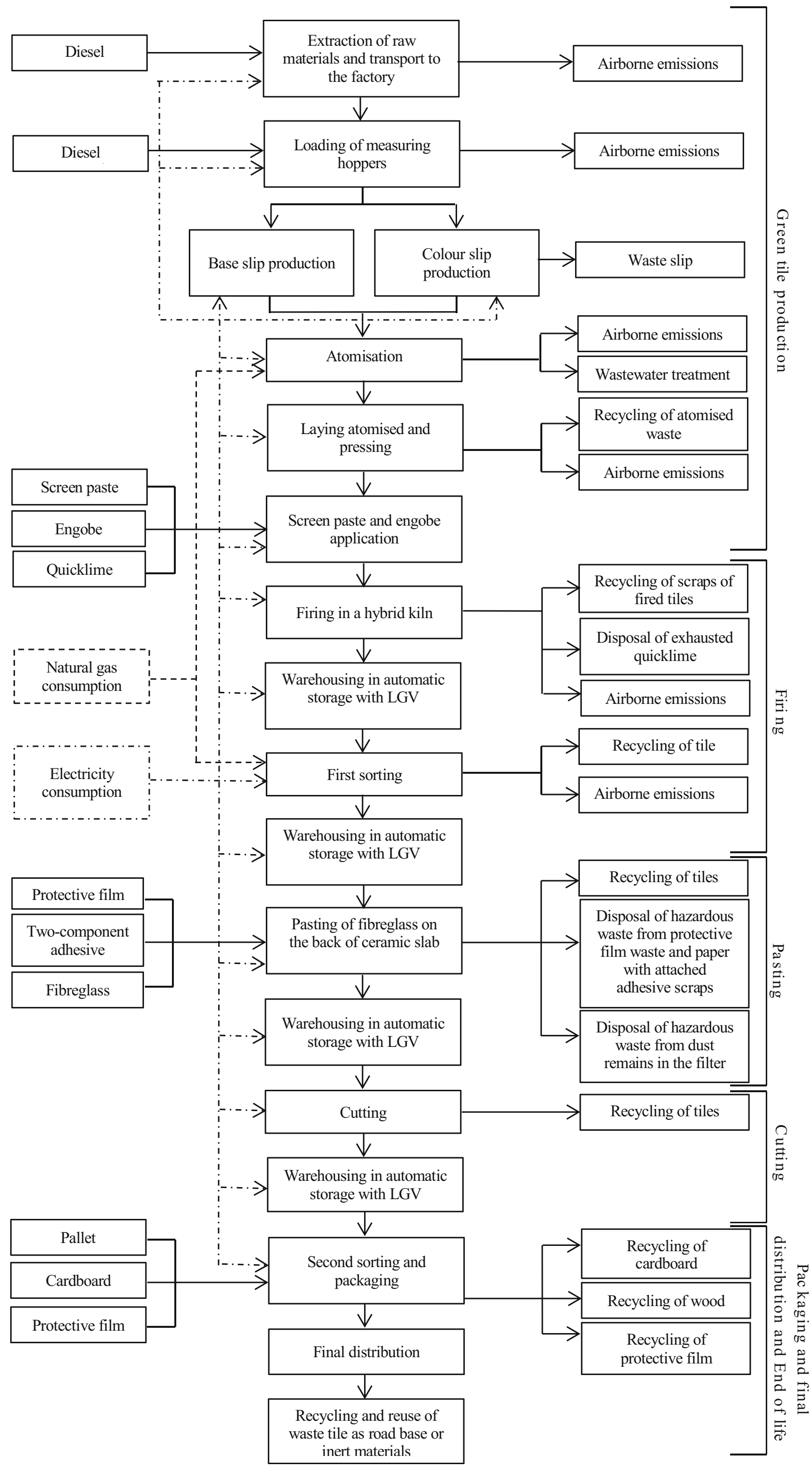
The tiles with the correct application of fibreglass are loaded onto a tray and brought to the automatic storage by LGV.

2.4 Cutting

Next, a tray is unloaded from the automatic storage by LGV and fed into the cutting line, where the following steps occur:

– Grinding, which removes glass fibres in the cutting lines, is performed by using an automatic tilter that operates at a max speed of 60 m/min. Then, an automatic tilter turns the slabs through 180°, so that the side without the backing is positioned on the cutting table for engraving on the upper side.
– Surface engraving is performed by a bridge CNC cutting table. Engraving is carried out by a laser system, which eliminates any contact with the ceramic surface.
– Cross-cutting the slab is performed in accordance with grinding–engraving lines in order to create the 1,000 mm×1,000 mm format. The head, tail and side trimmings are disposed of by crushing belts. A wheel system aligns and transports the slab towards the dynamic cross-cutting machine which opens the incision by pressing the separator rollers. Then, the tiles are collected in bins and transported to a collection place; next, they will be passed on

Fig. 1 Large, thin ceramic tile life cycle



to authorised plants. At the cutting line exit, the tile is detached with a variable speed motorised roller.

The 1,000 mm × 1,000 mm sized tiles with fibreglass backing are finally loaded onto a tray and returned to the automatic storage by LGV.

2.5 Packaging, final distribution and end of life

Finally, an LGV unloads slabs from the automated warehouse and feeds them into the packaging line, where they are checked according to geometric features and dimensional tolerances, such as the length, width, thickness, straightness

Table 3 Base and coloured slip compositions

	Value (%)
Base slip	
Water	34.7
Clay	19.3
Feldspars	45
Deflocculant	1
Coloured slip	
Water	30
Pigment	61.6
Clay	8.4

of sides, angles and planarity, and divided into first, second and third choice. As a consequence, different cardboard and packaging are used on the basis of the group. One cardboard box contains three 1,000 mm×1,000 mm sized tiles. The cardboard boxes are packed onto EUR-pallets in groups of 25 items per pallet. Finally, a polyethylene film is wrapped around them to protect the products. The tiles are then delivered to various customers according to the order book. Tiles are considered as an inert material for recycling as road foundations at the end of their useful life.

3 Methods and assumptions

3.1 Goal and scope definition

The goal of the study is to assess the environmental impacts of a large, thin ceramic tile reinforced with a fibreglass backing produced by Laminam S.p.A., in order to identify the hot spots in the system, with a particular focus on potential energy consumption and on the amount of GHGs emitted during the entire life cycle.

3.2 System, functional unit and function of the system

The company produces many different types of thin slabs, varying in dimension, decoration, size and colour. For the purpose of this study, the functional unit chosen is 1 m^2 of a black, large, thin ceramic tile reinforced with fibreglass backing (size 1,000 mm×1,000 mm×3.5 mm).

The function of the system is as floor and wall coverings for many indoor and outdoor applications, such as the building industry, ventilated facades, motorway infrastructure, galleries including in the photovoltaic field, furniture industry, etc.

3.3 System boundaries

The system boundaries cover the entire life cycle of the system analysed, in accordance with the LCA methodology. As can be seen in Fig. 1, the analysis includes raw material extraction and utilisation in green tile production; firing of the green tile to produce the large, thin ceramic tile; pasting of the fibreglass backing onto the back of ceramic tile; cutting of the ceramic slab into 1,000 mm×1,000 mm sized items; packing; final distribution; and end of life. The production, maintenance and disposal of facilities as well as the environmental burdens related to the production of chemicals, additives, adhesives, packaging and other auxiliary materials are also included in the present study. Emissions into the air and water as well as the solid waste produced in each step are all taken into account. The transportation of the solid waste to a treatment facility is also taken into account. As mentioned above, only the installation and use step are excluded. The following assumptions are made for the system studies:

- Particulate emissions into the air in the production of the base and coloured slip are assumed to be 0.1 % of the clay and feldspars input into the hoppers.
- The final distribution is assumed to be a scenario of 100 km from the producer to the customers, as is required by the Environmental Product Declaration (EPD) (EPD 2008).
- The electrical energy supply is assumed to be the Italian mix electrical energy generated by Ecoinvent.

3.4 Data quality and impact assessment methodology

Primary data concerning the amount of raw materials, the machineries, emissions, waste materials and packaging have been directly collected from Laminam S.p.A. Where the data have been missing, the study has been completed on the basis of information obtained from the Ecoinvent database (Ecoinvent v2 2009) that have been used to model the background processes (land use, materials production, fuel and electricity production and transports). The analysis is conducted using the SimaPro 7.1.8 software and IMPACT 2002+ evaluation method to assess the environmental impacts.

3.5 Life cycle inventory

Primary data refer to the 2008 annual production of the ceramic industry that is the subject of the study. Firstly, an accurate mass balance was created. The inputs (i.e. materials, water and energy resources) and outputs (i.e. airborne and waterborne emissions and solid waste) of the system were estimated starting from the annual data, such as the fired tiles, the annual square metres sold in the 1,000 mm×1,000 mm

format and the percentage of waste derived from each phase. The plant production data are shown in Table 4.

For the upstream phase processes, the I/O data refer to the annual production of large, thin tiles (6,318 m^2/year), while for the downstream stages (pasting, cutting, packaging and final distribution), the I/O data refer to the annual sales of the 1,000 mm × 1,000 mm tiles (1,816 m^2). Table 5 shows some of the most relevant I/O data for the tile production.

The inventory data have been modelled in SimaPro 7.1.8, taking the Ecoinvent database as a reference to configure the inventory of some materials (i.e. fibreglass) and chemicals (i.e. deflocculant), natural gas, electricity, transport, infrastructure and machinery. Auxiliary processes, such as pigment, engobe, screen paste and natural rubber plates, were created from scratch using the primary data.

3.6 Impact assessment

Life cycle impact assessment (LCIA) results were obtained with IMPACT 2002+ method using SimaPro 7.1.8 to determine the environmental impacts related to the emissions released and resources consumed in the system under study (Jolliet et al. 2003). This impact assessment method covers more impact categories than other methods and includes more substances, but the following additions and modifications have been implemented in order to use a more representative index of the system considered:

- Land use has been estimated using basic indicators of both land occupation and transformation. In the present study, transformation to forest intensive, normal transformation to forest intensive and transformation to arable have been introduced.
- Mineral extraction is characterised in consideration of some additional resources such as silver, gravel, sand, lithium, bromine and water in ground derived from the category minerals of Eco-indicator 99 with the same characterisation factors.

Table 4 Plant production data

Annual production data	Quantity	Unit
Annual production of the final tiles with dimensions 1,000 mm × 3,000 mm	63,180	m^2/year
Annual production of the fired tiles (1,030 mm × 3,090 mm)	21,060	tiles/year
Metre squared of tiles with dimensions 1,000 mm × 1,000 mm	2,073.72	m^2/year
Annual sales of tiles with dimensions 1,000 mm × 1,000 mm	1,816	m^2/year

4 Results and discussion

4.1 Inventory analysis results

Firstly, a midpoint category interpretation is conducted being more appropriate to evaluate the environmental impacts of the various substances accounted in the life cycle inventory. Then, in order to compare the portions of the individual impact categories with reference to the damage categories, the impact assessment is also discussed at the end point level. In the life cycle analysis, in order to explore in predictive way the environmental loads due to the large, thin ceramic tile production solely, the EPD scenario of 100 km has been adopted in order to make independently the environmental analysis of distribution strategies which are a variable in function of the market trends. The environmental analysis is then conducted in consideration of a 100 km scenario for delivering 1,816 m^2 of large, thin tiles in a 1,000 mm × 1,000 mm format to the customers. However, the real mileage for final distribution would have been 3,084 km. The comparison of environmental impact for different final distribution scenarios shows that the environmental damage increases to 27.3 % with the 3,084 km scenario (Fig. 2). The impact categories that are mainly affected by the damage increase are carcinogens (+44 %), acidification and eutrophication (+38.6 %), ozone layer depletion (+31.9 %) and respiratory inorganics (27.6 %).

In the environmental analysis, damage of the product is kept separate from that attributable to the manufacturer strategy in order to emphasise the environmental loads due to the large, thin tile production rather than business decisions that may or may not improve the overall effect.

4.1.1 Midpoint analysis

The impact categories included in this study are shown in Fig. 3 and Table 6 with respect to the main life cycle phases included in the study.

The results highlight that the base slip production stage plays the major role in all the impact assessment categories. *Global warming* is primarily attributable to the firing process and, secondly, to the pasting process. The most significant contribution to the global warming impact category is mainly due to GHG emissions (88.56 %) belonging to the pasting process and, in particular, to the adhesive used to stick the fibreglass backing to the tile. With regard to the firing process, a 9.28 % contribution is due to GHG emissions, which are generated by the firing phase as a consequence of the natural gas consumption necessary to feed the hybrid kiln.

Non-renewable energy is primarily affected by natural gas (38.47 %), heavy fuel oil (31.31 %) and uranium (11.3 %) emissions. About the first emission, the atomisation phase is the stage that produces the major environmental load

Table 5 Inventory data of a large, thin ceramic tile with advantageous technological properties

Category	Components	Quantity	Unit	Source of data
Energy input	Electricity consumption	235,403.44	kWh	Energetic processes I/O data derived from Ecoinvent database. Energy consumptions were supplied by the company
	Natural gas consumption	62,307	MJ	
	Input of raw material[a]	680,834.32	kg	Direct from the company
	Input of water (adds to raw materials)	358,263.73	kg	
	Output of kiln[b]	6,318	m^2	
	Input of first sorting phase[c]	2,073.72	m^2	
	Output of second sorting and packaging[d]	1,816	m^2	
	Quicklime	17,899.92	kg	
	Screen paste	156.37	kg	
	Engobe	2.35	kg	
	Protective film	142.8	kg	
	Two-component adhesive	615.89	kg	
	Cardboard	107.78	kg	
	Fibreglass	615.89	kg	
	EUR-pallet	435.83	kg	
	Wood packaging elements	263.44	kg	
	Plastic protective films	38.74	kg	
Emissions to air	Particulates <2.5 μm	26.65	g	Direct from the company
	Particulates >2.5 and <10 μm	9.36	g	
	NO_x	54.05	g	
	VOC	9.68	g	
	SO_x	59.51	g	
	Fluorine	2.48E-3	g	
	Heat, waste	227.94	MJ	
Transport	Road	9,193.3	km	Transport processes I/O data derived from Ecoinvent database. Transport distances were supplied by the tile company, and it was considered that the transport in the distribution phase was of 100 km
	Freight	5,667.5	km	
	Rail	924	km	
Waste to treatment	Waste from slip production	680.83	kg	Waste treatments were derived from Ecoinvent processes. Transport to disposal plants was considered too
	Atomised dusts retained by filter	17,805.06	kg	
	Moisture lost in the atomisation phase	358,263.73	kg	
	Wastes from green tiles	111,606.62	kg	
	Waste from fired tiles	60,232.86	kg	

[a] Total of clay, feldspars, pigment and deflocculant necessary to produce 6,318 m^2 of large, thin slab with dimensions 3,000 mm×1,000 mm

[b] Slabs with dimensions 3,000 mm×1,000 mm

[c] Slabs with dimensions 3,000 mm×1,000 mm necessary to produce 1,816 m^2 of tiles with dimensions 1,000 mm×1,000 mm

[d] Tiles with dimensions 1,000 mm×1,000 mm

(27.75 %) because of heat energy consumption in the spray drier. About the second emission, the base slip production is the step that contributes to the highest bounder (36.75 %), particularly caused by the transport of raw materials. Indeed, the coloured slip production accounts for 25.76 %, especially for pigment manufacture.

Pasting and coloured slip production are the subsystems that contribute most to *mineral extraction*. The first process is

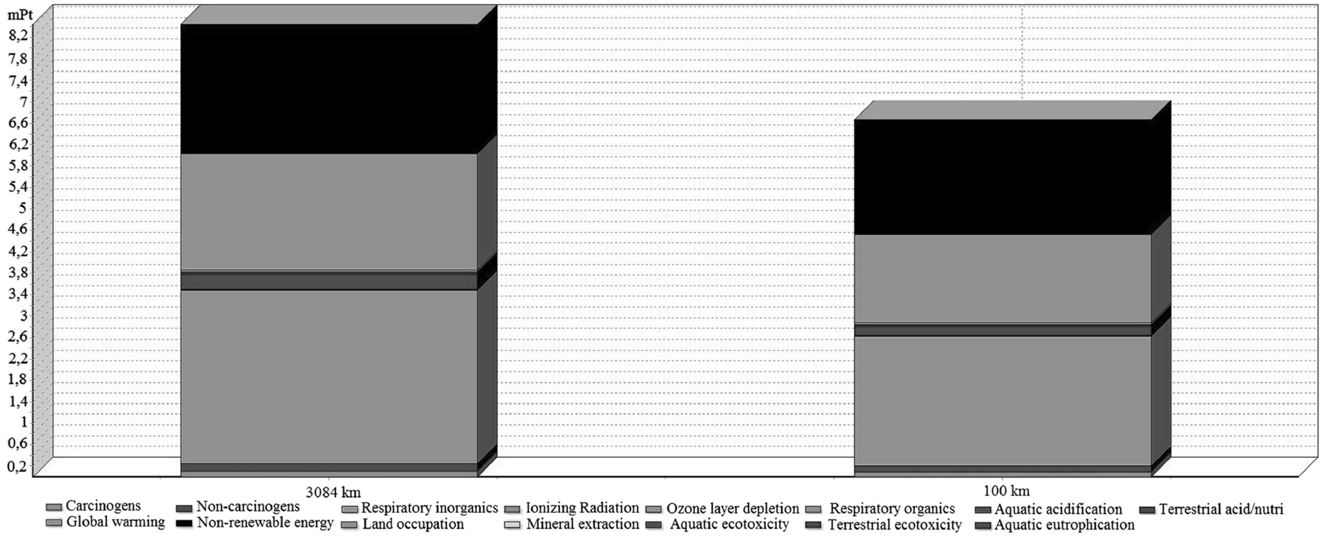


Fig. 2 Comparison of environmental impact values (Pt) for different final distribution scenarios

dominated by the release of water, cooling and unspecified natural origin (36.13 %) while the latter process by the release of chromium and nickel in ground for 16.7 and 12.87 %, respectively, due to the pigment manufacture.

The *carcinogen* impact category is affected by the release of hydrocarbon aromatic in air (73.6 % of the total impact) generated during the pasting process in the production of the two-component adhesive and by dioxin emissions (6.9 %), attributable to second sorting and packaging, particularly in the corrugated board manufacture. Moreover, *non-carcinogenic* effects are caused by heavy metal emissions into the water and air. The 34.43 % of direct arsenic emissions to water are related to the transport of the raw materials used in the base slip production, and 28.4 % of direct arsenic emissions to air are generated by the fibreglass production from the pasting phase.

The major contribution to *respiratory inorganics* is due to 48.21 % of particulate emissions generated during the base slip production, 25.81 % of NO_x released from barges transporting the raw material and 17.40 % of SO_2 emissions released from pigment production in the coloured slip production. For *respiratory organics*, the base slip production causes the greatest environmental load, being responsible for the release of propene into the air (99.39 %) and for non-methane volatile organic compound (NMVOC) emissions into the air

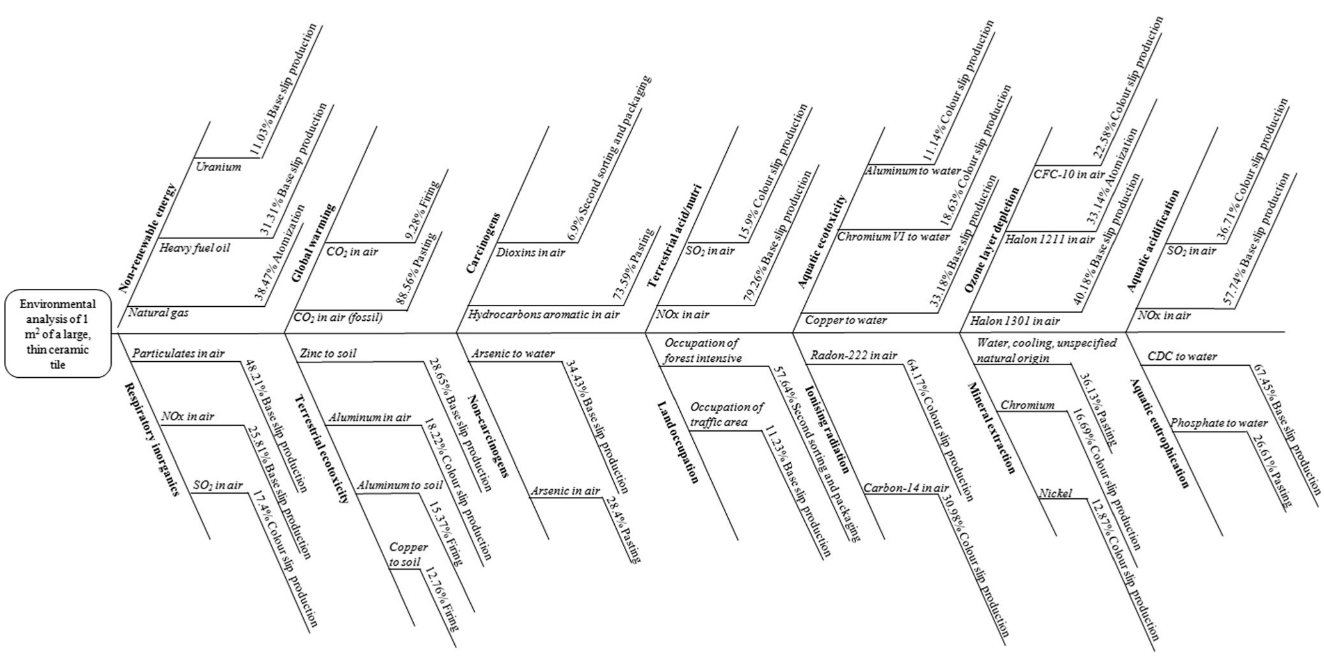


Fig. 3 Effects of the substances on the impact categories and the processes that generated them

Table 6 Characterised LCIA results

Damage category	Impact category	Unit	Total	Base slip production (%)	Coloured slip production (%)	Atomisation (%)	Pressing (%)	Screen paste application (%)	Engobe application (%)	Firing (%)
Human health	Carcinogens	kg C_2H_3Cl	215.4E-3	11.37	9.527	7.703	3.815	0.706	0.323	6.815
	Non-carcinogens	kg C_2H_3Cl	383.7E-3	15.441	13.591	1.340	2.870	0.555	0.277	6.349
	Respiratory inorganics	kg PM2.5	26.65E-3	42.297	17.167	1.520	1.751	0.497	0.323	8.367
	Ionising radiation	Bq C-14	295.44	14.652	28.211	2.629	1.676	0.925	0.570	17.994
	Ozone layer depletion	kg CFC-11	1.87E-06	17.578	32.386	13.167	0.754	0.503	0.405	16.324
	Respiratory organics	kg ethylene	4.33E-3	86.879	1.568	0.740	0.131	0.084	0.042	1.881
Ecosystem quality	Aquatic ecotoxicity	kg TEG water	2728.47	19.019	32.057	1.452	2.699	0.548	0.360	13.667
	Terrestrial ecotoxicity	kg TEG soil	322.42	24.199	18.979	2.014	1.459	0.879	0.601	19.649
	Terrestrial acidification/nutrification	kg SO_2	374.3E-3	31.715	17.739	2.511	0.827	0.544	0.360	11.723
	Land occupation	m^2 org. arable	403.2E-3	12.160	5.806	0.237	1.711	1.590	1.540	1.978
	Aquatic acidification	kg SO_2	103.1E-3	19.527	30.625	2.498	0.896	0.624	0.447	13.842
	Aquatic eutrophication	kg PO_4 P-lim	1.13E-3	17.554	8.718	1.093	1.616	8.481	0.417	8.815
Climate change	Global warming	kg CO_2	16.32	16.816	15.825	10.467	1.086	0.671	0.487	22.096
Resources	Non-renewable energy	MJ primary	284.71	18.547	13.619	11.433	0.956	0.747	0.439	19.396
	Mineral extraction	MJ surplus	1.151	10.253	35.253	1.627	1.593	1.207	0.446	16.125

Damage category	First sorting (%)	Pasting of fibreglass (%)	Cutting (%)	Second sorting and packaging (%)	Final distribution and end of life (%)	Building (%)	LGV (%)	Automatic storage (%)
Human health	0.063	34.719	0.206	4.899	0.934	2.459	11.77	4.688
	0.058	36.694	0.197	6.347	2.210	1.748	8.539	3.784
	0.066	18.288	0.255	3.077	1.509	1.164	2.420	1.299
	0.138	18.892	0.535	6.114	0.993	1.074	4.104	1.492
	0.100	9.899	0.394	3.628	2.073	0.604	1.443	0.742
	0.010	6.018	0.039	1.226	0.542	0.266	0.361	0.213
Ecosystem quality	0.081	13.588	0.295	2.711	2.749	0.975	6.269	3.529
	0.147	12.614	0.585	6.242	3.557	1.743	5.624	1.707
	0.089	22.432	0.349	4.196	2.777	2.059	1.638	1.042
	0.009	3.243	0.032	68.446	0.427	1.994	0.537	0.291
	0.110	21.906	0.433	3.428	1.694	1.352	1.823	0.794
	0.079	32.928	0.298	12.314	1.943	0.773	3.016	1.954
Climate change	0.120	22.112	0.469	4.591	1.565	0.880	1.863	0.952
Resources	0.107	24.315	0.420	4.937	1.499	0.716	2.022	0.848
	0.099	22.252	0.415	3.798	0.543	1.853	2.998	1.537

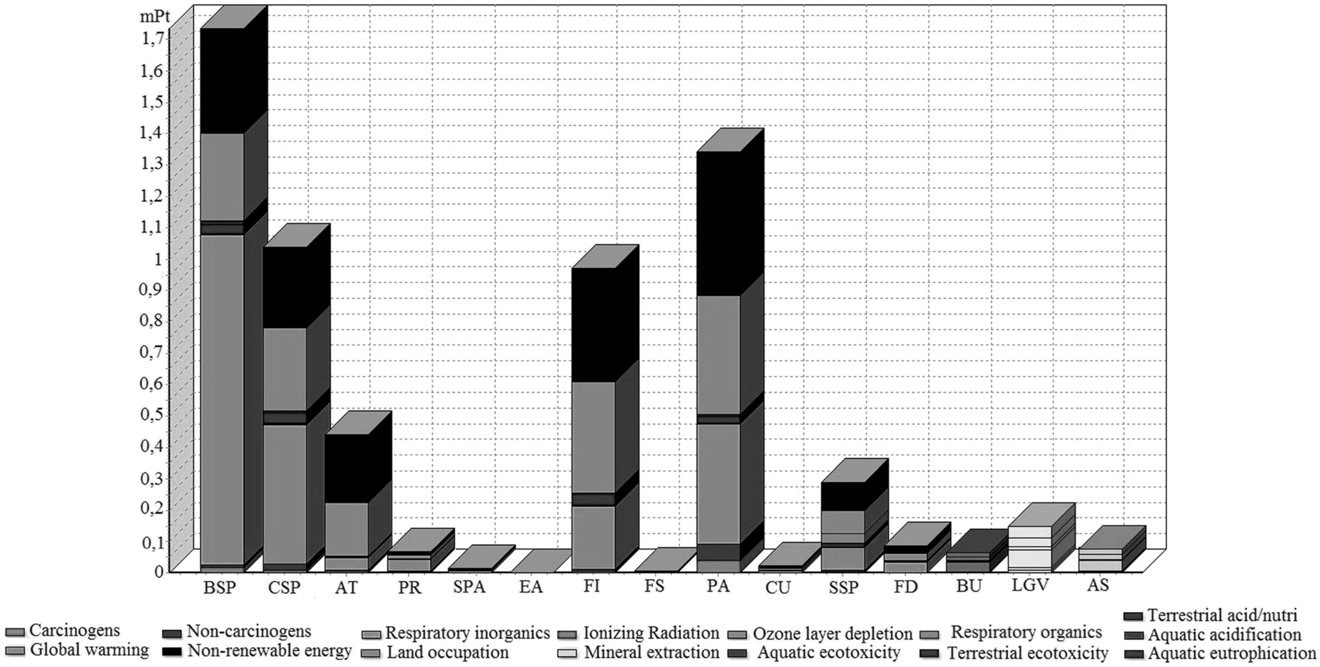


Fig. 4 Evaluation by impact categories of 1 m^2 of a large, thin ceramic tile (3,000 mm×1,000 mm). *BSP* base slip production, *CSP* colour slip production, *AT* atomization, *PR* pressing, *SPA* screen paste application, *EA* engobe application, *FI* firing, *FS* first sorting, *PA* pasting, *CU* cutting, *SSP* second sorting and packaging, *FD* final distribution, *BU* building, *LGV* laser guide vehicle, *AS* automatic storage

(32.14 %) caused by the deflocculant production and by the transport of raw materials, respectively.

Copper emissions to water, generated by the base slip production and in particular the transport of raw materials, and chromium VI and aluminium emissions to water, released by pigment manufacture in the coloured slip production, affect the *aquatic ecotoxicity* category (33.18, 18.63 and 11.41 %, respectively). In the *ionising radiation* category, the emissions to air of radon-222 and carbon-14 account for 64.17 and 30.98 %, respectively, both released by the pigment production in the coloured slip production.

The *ozone layer depletion* effects are attributable for the 40.81 % to the Halon 1301 released to air due to the transport of the raw materials in the base slip production, 33.14 % to Halon 1211 released during the atomisation phase and 22.58 % to the CFC-10 released to air generated by the pigment manufacture in the coloured slip production.

NO_x and SO_2 emissions to air form the most significant contribution to the *terrestrial acidification*/*nutrification* (79.26 and 15.9 %, respectively) and to the *aquatic acidification* (57.74 and 36.71 %, respectively) impact categories. The greatest contribution to the *aquatic eutrophication* potential is derived from the COD emissions to water (67.4 %) due to the transport of the raw material used in the base slip production phase and to the phosphate emissions to water (26.61 %) from the two-compound adhesive production in the pasting phase. The largest contribution to *land occupation* comes from the occupation of forest intensive (57.64 %) due to the use of EUR-flat pallets in the packaging step and the occupation from the traffic area (11.23 %) required to transport the raw materials in the base slip process. Figure 4 shows the evaluation by single score and impact categories of 1 m^2 of a large, thin ceramic tile.

4.1.2 End point analysis

The results of the damage assessment, reported in Table 7, show that damage to *human health* is due to the effects of inorganic emissions (91.05 %) caused by particulate emissions (43.89 %) and NO_x to air (23.5 %) that are released during the base slip production, which produces the major damage (40.09 %) in this category. The effects on terrestrial ecotoxicity influence the overall *ecosystem quality* (72.53 %), and the damage is mainly due to zinc emissions to soil (20.81 %), aluminium to air (13.54 %) and aluminium to soil (11.47 %). Also in this case, the process that contributes to the

Table 7 Characterisation and evaluation of the life cycle

Damage category	Unit	Total
Human health	DALY	2.05E-05
Ecosystem quality	PDF/m^2/year	3.51
Climate change	kg CO_2	16.32
Resources	MJ primary	285.86
Single score	Pt	6.6675E-3

highest impact is the base slip production. The damage to *climate change* is generated by the emissions of 16.32 kg $CO_{2(eq)}$. The consumption of natural gas (38.33 %), crude oil (10.98 %) and uranium (10.98 %) in energy supply processes affects the *resources* category, where the depletion of non-renewable energy resources produces the most damage (99.6 %) and pasting is the process that has the major effect in this category.

Single score damage is 6.667E-3 Pt for 1 m^2 of a large, thin tile (Table 7). The total damage is caused by 43.28 % to human health, 28.18 % to resources, 24.69 % to climate change and 3.85 % to ecosystem quality. Base slip production is the process mainly responsible for the total damage (27.62 %), together with pasting (21.31 %), followed by the coloured slip production (15.69 %) and firing processes (15.1 %). The atomisation phase and the packaging and final distribution step make a minor contribution (6.6 and 4.48 %, respectively) to the environmental damage.

5 Conclusions

The impact assessment results reveal the hot spots of the whole life cycle of large, thin ceramic tiles coupled with a fibreglass backing, introducing advantageous technological properties. The following conclusions are drawn and recommendations are made:

- The phases of the life cycle with the highest environmental burdens are the base slip production (27.62 %) and the pasting process (21.31 %).
- Particulate and NO_x emissions, released from base slip production and the pasting phase, affect the respiratory inorganics category. Indeed, the crude oil consumption, for the transport of the raw materials in base slip production, and the natural gas used to manufacture the two-component adhesive in the pasting step, have the highest impact in non-renewable energy. The same processes release the GHG emissions which affect the global warming impact category. In expanding the assessment to the whole life cycle, the step that produces the highest environmental load and contribution in the global warming category is the firing step due to the use of natural gas.
- Better environmental performance can be achieved by reducing waste materials and, therefore, the amount of all the materials necessary for the production of the large, thin tile, especially those associated with the highest impact, such as the two-component adhesive, containing polyurethane and isocyanate MDI, the pigment consisting of iron-chromium oxides and the deflocculant containing acrylic acid.
- Product comparison is possible when product category, data quality, assumptions, functional unit, system bounders, life cycle phases included in the system bounders and system function are the same in both life cycles of compared products. The comparison between the investigated system and the traditional stoneware tile cannot be carried out since the above-mentioned conditions are not respected. For example, Ibáñez-Forés et al. (2011) studied a single-fired stoneware, but data gathered from 35 Spanish enterprises which reflect the Spanish and not the Italian context have been used; again, Nicoletti et al. (2002) assessed a single-fired ceramic tile, but statistic data of Italian ceramic district and no data related a specific company have been considered. In these cases, data quality is different than data quality of analysed product. Furthermore, Tikul and Srichandr (2010) studied the environmental performance of a double-fired glazed tile, but they adopt a “from gate to gate” scenario as system boundaries and no “from cradle to grave” scenario. In this case, the life cycle steps included in the life cycle analysis are different than those considered in the present study.
- A rationalisation of the supply chain by minimising the distance from the supplier to the ceramic industry reduces the damage caused by the transport of the raw materials and by the chemical components that is a decisive process for environmental performance.
- Identification of critical phases characterised by an excessive consumption of energy, such as the internal transport executed by LGV, which, as mentioned above, loads tiles into the AS and subsequently unloads them for further processing.

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